Radio Frequency Energy Harvesting From Ambient FM Signals for Making Battery-Less Sensor Nodes For Wireless Sensor Networks

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***Abstract*—This paper presents an efficient rectifier for Radio Frequency (RF) energy harvesting applications in FM band (88MHz to 108MHz). The proposed rectifier is based on Modified Greinacher Rectification topology. The circuit is designed on Keysight Advance Design System (ADS) and realized on a 1.6mm thick FR4 sheet with 35um of copper cladding. Schottky diode, HSMS2850 is used as rectification element and lumped components are used for impedance matching. Power levels of interest are from -30dBm to 0dBm. The rectifier operates optimally for a load range of 10kΩ to 75kΩ with maximum RF to DC conversion efficiency of 74.8% for 5dBm input power at 96 MHz.The conversion efficiency for entire FM band for -10 dBm input is around 50% which is the typical input power level of ambient wireless signals. Measurements show excellent agreement with the simulated results. The proposed rectifier has harvested 12.77 uW of DC power from an input of -14.2dBm channel power with an overall efficiency of 33.59% in FM band.**

Keywords—Ambient sources;FM band;impedance matching;rectifier;RF energy harvesting

I. INTRODUCTION

With the advent of Wireless Sensor Networks (WSNs), development of self- sustainable battery-less sensor nodes has become an active research area. Different mechanisms are being investigated to supply wireless power to the sensor nodes of WSNs and replace batteries from them which will save the maintenance cost and labor. Long range coverage and omnipresence of ambient RF signals make RF Energy Harvesting as one of the most suitable ways to achieve this objective [1]. Investigations have been done to design various rectennas to harvest DC power from different RF bands present in the ambient environment. The authors in [2] have featured a dual band rectenna that harvested DC voltage from GSM1800 and UMTS2100 bands. By using the multiband approach in [3] a stacked RF energy harvester was proposed which can harvest energy from GSM900, GSM1800, UMTS2100 and Wi-Fi bands. Authors in [4] have featured a novel six-band rectenna which also incorporated lower bands of 550MHz and 750MHz along with the four others published in [3].

FM band is used to broadcast radio channels throughout the world. Its omnipresence, lesser free space path loss, easier circuit design and cheap electronic components are attractive features to use it for RF energy harvesting but in these recent developments FM band is not utilized. Authors in [5] have proposed a RF energy harvester for FM band with a bandwidth of 3MHz (81.9 MHz to 84.7MHz). According to the best of authors' knowledge no rectifier design has been reported which can operate at low power levels for the entire bandwidth of FM band (88MHz to 108MHz). This paper focuses on development of a highly efficient, low threshold and wideband rectifier to harvest DC power from ambient FM band signals. The rest of the paper is organized as follows: Section II describes the design of the rectifier, Section III analyzes the performance of the proposed design, Section IV shows the results of measurement and Section V concludes the paper.

II. DESIGN OF RECTIFIER

A. Topology of Rectifier

Voltage multipliers are considered as best choice for RF energy harvesting because of their high efficiency and simple designs [1]. Due to the same merits, a Modified Greinacher Rectifier topology (shown in Fig.1) was chosen in this study. Two voltage doublers are differentially connected to form this topology. Modified Greinacher Rectifier has smaller input impedance as compared to simple voltage doubler which results in ease in impedance matching **[6]**. The differential configuration results in reduced harmonic content, better power handling capability and lesser loss in capacitors **[6]**. The diode used for rectification is HSMS-2850 by Avago Technologies.

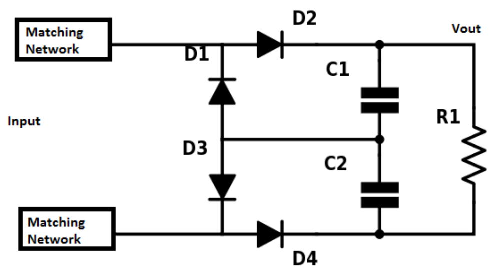


Fig. 1 Modified Greinacher Rectifier Topology with Impedance Matching

B. Impedance Matching

Impedance matching is a crucial stage in rectifier design because of the non-linear behavior of rectifier. If the impedance of the rectifier is not matched to the antenna (which is generally 50Ω) the incident wireless signals will be reflected to the environment which shall result in decrease in efficiency of the RF energy harvester. The input impedance of a rectifier is function of frequency of operation, input power and load connected at the output. To get a better insight of this non-linear behavior a Modified Greinacher Rectifier was designed in ADS. Non-linear model of the diode HSMS2850 was imported in design from HF Diode Library of ADS. Chip capacitors (C1 and C2) of 100nF were used in this design and were modeled by using SPICE files provided by Murata. The layout for rectifier was designed in Momentum and was co-simulated to include the non-linear effects. The circuit was simulated using Harmonic Balance (HB) simulation controller. Real and imaginary values of impedance were noted for power levels -30dBm to 0dBm in the desired frequency range (88MHz to 108MHz). A third order lumped component based matching network shown in Fig. 2 was chosen for each branch. Initial parameters of the matching network were calculated for the following values of input impedance; 1636-j1298Ω @88MHz and 1378-j1325 Ω for -20 dBm and 1685-1622jΩ@ 88MHz and 1346-1585jΩ @108 MHz for -30 dBm input power for a load resistor of 10kΩ using Smith Chart Utility in ADS. In the next step network was optimized for entire power range (-30dBm to 0dBm) and load range (10kΩ to 75Ω) using Optimization Utility in ADS. The optimized values for components of matching network are shown in Table I. The realized prototype of the proposed rectifier is shown in Fig 3.

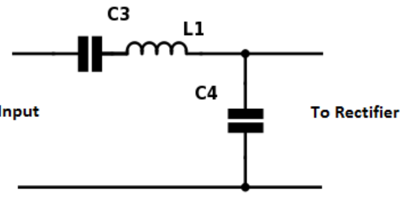


Fig. 2 Proposed Impedance Matching Network for each branch

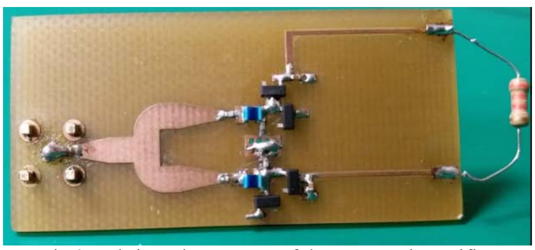


Fig 3. Fabricated Prototype of the Proposed Rectifier

TABLE I
OPTIMIZED PARAMETERS FOR THE PROPOSED MATCHING NETWORK

Component	Upper Branch	Lower Branch
C3	8.2pF	47000pF
L1	820nH	820nH
C4	3pF	2.7pF

III. PERFORMANCE ANALYSIS

The simulated and measured reflection coefficients (S11) for the proposed rectifier are shown in Fig. 4. It can be seen in fig.4a that the proposed rectifier is matched in FM band for multiple power levels (-10dBm to-30 dBm) and hence it can be used with ambient FM band signals which always have a varying power level. Fig4b shows that the proposed rectifier is matched for a diverse load range (10kΩ to 75kΩ) and it can supply DC power to variety of wireless sensors and loads. Both traits make the proposed rectifier a perfect fit for RF energy harvesting applications.

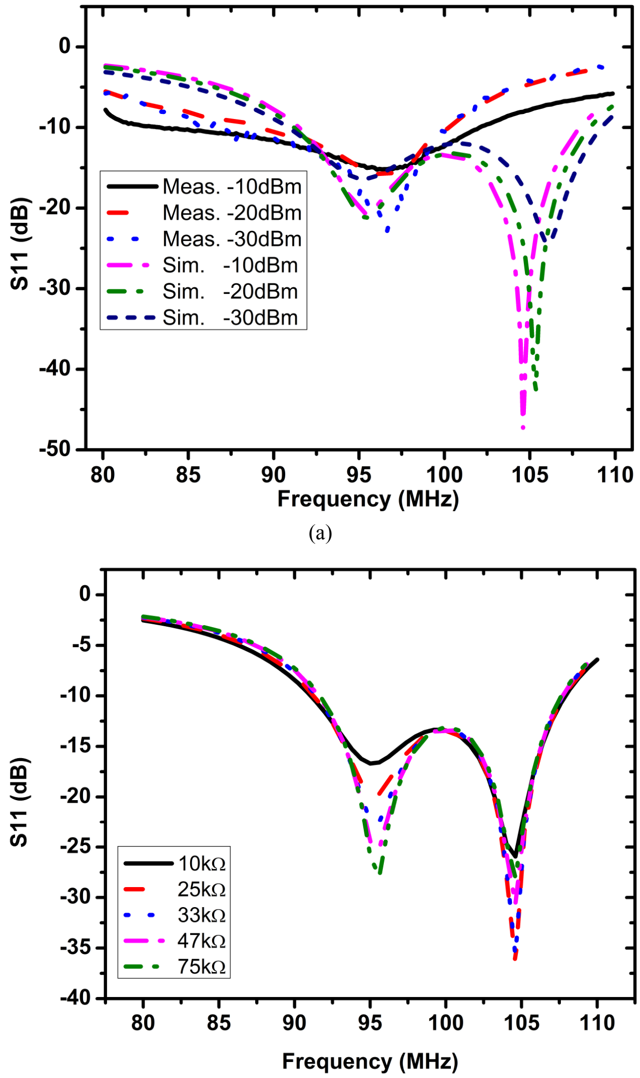


Fig. 4 S11(dB) of the proposed rectifier (a) measured and simulated for multiple input power levels when R_L=10kΩ (b) simulated for multiple loads when Pin=-15 dBm

The key performance indicator of a rectifier is its RF to DC conversion efficiency (η_{conv}) which is described in “equation (1)”.

It shows the capability of a rectifier to produce output DC power.

$$\eta_{conv} = P_{out}/P_{in} \qquad (1)$$

Where, P_{in} is the input power to the rectifier and P_{out} is the output DC power generated by the rectifier and is described by "equation (2)"

$$P_{out} = (V_{out}.I_{out})/R_{Load} \qquad (2)$$

V_{out} is output voltage across the load resistor and I_{out} is the current through it.

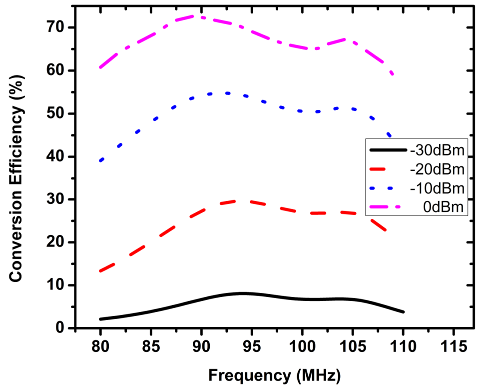
The simulated and measured conversion efficiency of the proposed rectifier is shown in Fig 5. It can be seen that in fig.5a that the conversion efficiency is almost constant for entire FM band at different power levels and hence it can maintain excellent performance at different frequencies and varying power levels and is fit for real world conditions. The conversion efficiency is around 50% for entire FM band at -10dBm power level which implies that it is very efficient at low power and makes it a very good candidate for energy harvesting applications. Fig5b shows that the maximum conversion efficiency of the proposed rectifier is 74.8% for 5dBm input power. This implies that the proposed rectifier is also efficient for higher power levels and it can also be used for RF to DC conversion in applications which involves dedicated power sources and wireless power transfer. The efficiency reduces at higher power levels (above 5dBm) due to the break-down of the diode.

The literature available for RF to DC conversion in FM band is very limited because it hasn't been investigated for RF energy harvesting. Table II shows comparison of this work with some related designs and in terms of varying power level, bandwidth of operation and output load range the proposed rectifier is better than the other published designs because they haven't reported the performance under changing power levels, output loads and are not matched for entire FM band.

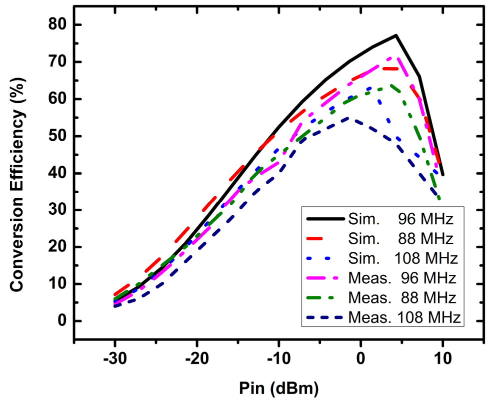
TABLE II
COMPARISON WITH THE RELATED WORK

Ref	Bandwidth	Power Levels of Interest	Load Range	Efficiency at Pin=-10 dBm
[5]	81.9 to 84.7 MHz	-20 dBm	NR	NR
[6]	100 MHz	0dBm to 35dBm	NR	NR
[This Work]	**88 to 108 MHz**	**-35dBm to 0dBm**	**10-75 kΩ**	**53% @ 90MHz** (Max. Efficiency 74% @ 5dBm input power)

* NR: Not Reported



(a)



(b)

Fig.5 Conversion Efficiency of the proposed rectifier (a) Conversion Efficiency vs Freq (b) Conversion Efficiency vs Input Power for Multiple Frequencies

IV. MEASUREMENT WITH ANTENNA

Having optimized the rectifier to work with low power signals of FM band and for a wide output load range the proposed rectifier was tested with an antenna to analyze its performance with wireless signals. First, ambient signal strength of FM spectrum was measured on top of a building with a handheld spectrum analyzer (PSA-2702). The received spectrum is shown in Fig. 6. The received spectrum received was exported to MATLAB for calculating the channel power using the 'bandpower' function. The total channel power residing in FM band was -14.2 dBm. The ambient signal strength is always varying because the incident signals are suffering various multipath reflections. To test the proposed rectifier and analyze its performance, FM spectrum with similar channel power was emulated in lab using Rhode and Schwarz Vector Signal Generator. A general-purpose antenna, PSA Ant2 (gain 2.15 dBi) was connected to the rectifier and it was placed at 10m distance from the transmitting end. The total transmit power was 20dBm which was distributed in 8 tones at multiple frequencies. The spectrum received at 10m distance from the transmitting end is shown in fig.6. At this distance, the channel power received by the antenna was roughly the same as measured in ambient environment and the output voltage

measured was 0.619V (shown in Fig. 7) across a 30kΩ resistor. The total DC power harvested was 12.77uW with an overall efficiency of 33.59%. The harnessed DC power can be used to power a variety of low power sensors.

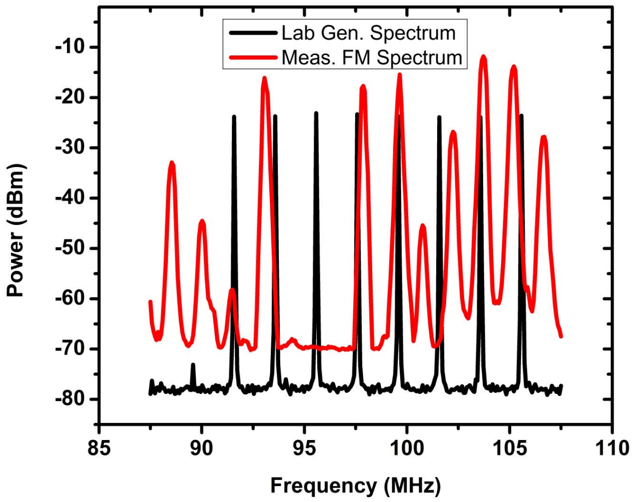


Fig. 6 Measured FM band spectrum in ambient environment and lab generated FM band for testing of the proposed rectifier

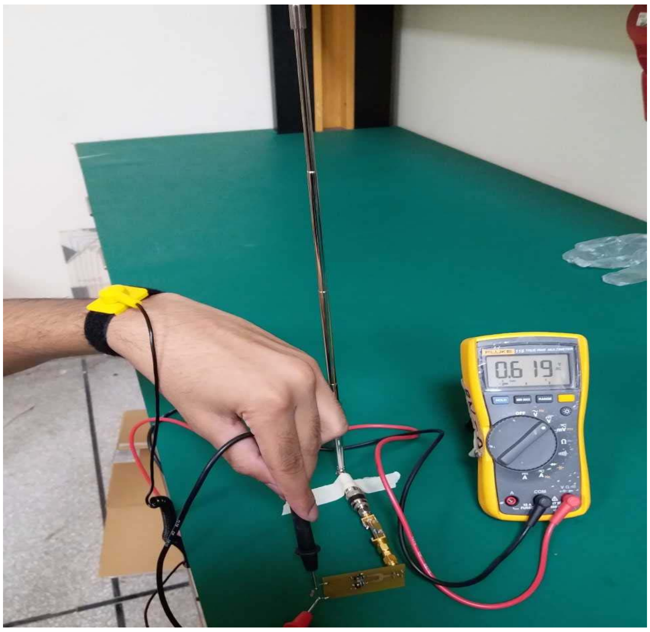


Fig. 7 Measurement of output voltage generated by proposed rectifier for -14.2 dBm input power

V. Conclusion

A highly efficient and low threshold rectifier is presented for harnessing DC power from ambient wireless signals of FM band. The proposed design is optimized for operation in various conditions such as varying power levels of signals and wide range of loads. The rectifier operates optimally at lower power levels and maintains a flat efficiency of 50% at -10dBm input power level for all the frequencies of FM band (88MHz to 108MHz). The proposed design has an excellent power handling capability it has a maximum RF to DC conversion efficiency of 74.8% for 5dBm input power at 96 MHz. To the best of authors' knowledge this work is the first study which has proposed a rectifier which maintains excellent performance in various conditions for entire FM band. This work will pave the way for developing various real world wireless energy harvesting circuits and battery-less sensor modules for wireless sensor networks.

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